SPIN PHYSICS

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We review recent experimental and theoretical progress in spin physics, as presented in the spin parallel session of DIS2006. In particular, we discuss the status of the nucleon spin structure, transverse polarized asymmetries, and recent developments such as DVCS, polarized fragmentation and polarized resummation.

1. The polarized structure of the nucleon

Experimental and theoretical studies of spin physics in the last several years have considerably widened their scope. Inclusive polarized deep-inelastic measurements, and their interpretation in terms of polarized quark and gluon structure functions, are now supplemented by measurements of semi–inclusive processes, heavy quark production and high–P_T hadron production and deeply–virtual Compton scattering (DVCS) in electron–nucleon scattering, by data collected in a variety of hard processes at the polarized hadron collider RHIC, and by data on polarized fragmentation from e^+e^- machines. Their interpretation requires both a deepening and a widening of available theoretical tools. On the one hand, the wealth of new data on the spin structure of the nucleon requires the use of the more advanced techniques that are being developed in the unpolarised case for the dscription of the parton structure of hadrons, specifically in view of the LHC:[1] higher order QCD computations, resummation, global parton fits with errors. On the other hand, new quantities must be introduced, along with their theoretical interpretation within QCD: polarized fragmentation functions, transverse momentum distributions and orbital angular momentum,

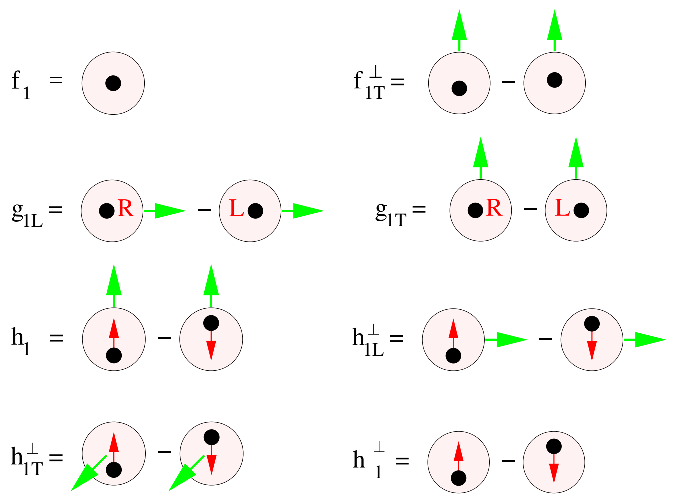

Figure 1. Various polarized distributions. he outer arrows denote the polarization of the nucleon, the inner ones the polarization of the parton. Horizontal arrows denote longitudinal polarization (i.e. along the direction of motion). (From Ref. [2])

transverse spin distributions and their cognates (see Fig. 1).

In this brief review, based on the presentations in the spin working group at DIS06, we will first review the status of the nucleon spin problem: we will summarize new determinations of the polarized parton distributions Δq and Δg in lepton scattering at CERN and DESY and in proton–proton scattering at RHIC, and first data on DVCS from JLAB, and we will discuss their theoretical analysis and interpretation. We will then summarize recent progress on transverse spin asymmetries: we will review several recent asymmetry measurements in hadron production at CERN, DESY AND RHIC, and future measurement for the Drell-Yan process at J-PARC and GIS, and we will reveiw recent progress in the formulation of a unified approach to transverse single–spin asymmetries ased on perturbative factorization. Finally, we will discuss several recent new developments which extend the range of experimentally accessible quantities and computational techniques to the polarized case: specifically, we will analyze measurements of polarized fragmentation and structure functions at low Q^2, and discuss the development of polarized resummation methods.

2. The nucleon spin puzzle

As well known, the nucleon spin problem[3] has to do with the fact that the quark spin fraction is measured to be small (at least, with the most straightforward definition of quark spin fraction). One may wonder why this is a problem: after all, the quark momentum fraction is also relatively small, of order of a half, and entirely due to the interaction (i.e. not to quark masses). Given the nucleon mass is not carried by the quark masses, and only partly by quark interactions, which should it surprize us if the nucleon spin is not carried by the quark spin? The answer is, of course,[4] that what is surprizing is the violation of the OZI rule: nucleon matrix elements of the singlet axial current are much smaller than those of the octet, i.e.

$$a_0 = a_u + a_d + a_s \ll a_8 = a_u + a_d - 2a_s, \tag{1}$$

where the axial charges a_i are just the forward quark current matrix elements from flavor i: $\langle N;\, p, s | J^{\mu}_{5,\,i} | N;\, p, s\rangle = a_i M_N s^{\mu}$.

Explanations of this situation fall in two broad classes: those which argue that the singlet is special, because, unlike the octet, it can couple to gluons, and those which argue that the octet is special, because strangeness in the nucleon is much larger than one might expect. Hence, in order to understand the spin puzzle one needs precise measurements of the gluon, strange and antistrange quark distributions, specifically their first moments.

It is important to remember that so far a_0 and a_8 have not been determined directly: rather, they are obtained from the combination of a direct measurement of a linear combination of them, and the indirect determination of an independent linear combination, obtained using SU(3) from baryon octet matrix elements of the axial current, determined by beta–decay rates. Given doubts on the accuracy of SU(3), a direct measurement of the nucleon axial charge for each flavor would be desirable: this, in turn, entails the determination of the first moment of all polarized light quark and antiquark densities, as well as of the polarized gluon density, that mixes in the singlet.

2.1. *Experimental results on* Δq *and* ΔG

New experimental results relevant for the determination of polarized parton distributions have been obtained recently both in lepton DIS (COMPASS and HERMES) and in proton-antiproton scattering (STAR and PHENIX).

At the inclusive DIS level, the COMPASS experiment presented A_1^d and

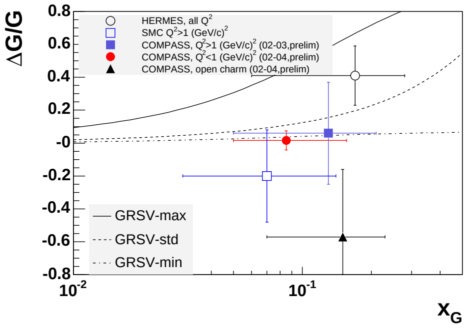

Figure 2. The gluon polarizations obtained by the COMPASS experiment from the semi-inclusive high-p_T hadron-pair measurement and open-charm measurement compared with those obtained by the SMC and HERMES experiments from the high-p_T hadron-pair measurement.

g_1^d results for $Q^2 > 1$ GeV^2. This new results improved their QCD analysis, and gave $\Delta\Sigma = 0.25 \pm 0.02$ (stat) and $\Delta G = 0.4 \pm 0.2$ (stat) at $Q^2 = 3$ GeV^2.

At the semi-inclusive level, the HERMES experiment obtained updated $\Delta s + \Delta\bar{s}$ distribution from their DIS measurement and semi-inclusive $K^+ + K^-$ measurement with the polarized-deuterium target. Since the strange quarks carry no isospin and the deuteron is an isoscalar target, they obtained $\Delta s + \Delta\bar{s}$ with two assumptions, isospin symmetry between proton and neutron, and charge-conjugatoin invariance in fragmentation. They also obtained the fragmentation functions needed in this analysis from multiplicities directly at HERMES kinematics with the same data. The result showed the strangeness suppression factor for $s + \bar{s}$ production is important for the $K^+ + K^-$ fragmentation function from non-strange quarks. The $\Delta s + \Delta\bar{s}$ distribution was shown to be consistent with zero with improved uncertainties.

The COMPASS experiment can access ΔG directly by three methods, high-p_T hadron-pair measurement at low Q^2, that at high $Q^2 > 1$ GeV^2, and that measured by open-charm measurement. The results shown in the right panel of Fig.2 prefer small ΔG or to have a node at $x \sim 0.1$. $\Delta G \sim 0.4$ is not excluded and scenario with a small orbital angular momentum in the nucleon is still possible. $\Delta G \sim 0$ indicates the important role of the orbital angular momentum.

First results relevant for the determination of ΔG were recently obtained

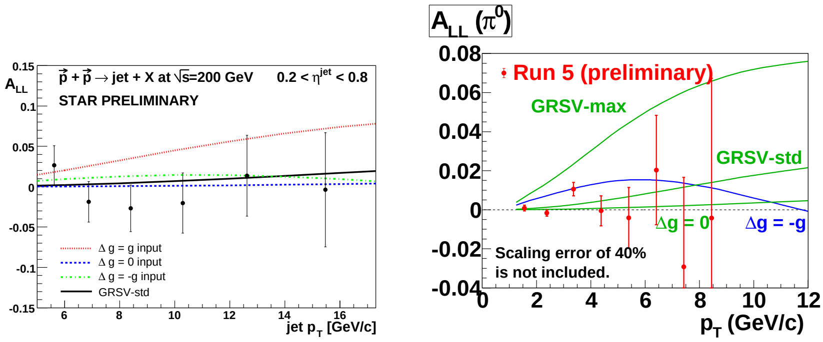

Figure 3. The double helicity asymmetry in the inclusive jet production measured by the STAR experiment (left) and that in the inclusive π^0 production measured by the PHENIX experiment (right) at midrapidity in polarized $p + p$ collisions

by RHIC experiments. The STAR experiment presented their preliminary result of the double helicity asymmetry in inclusive jet production at midrapidity in polarized $p + p$ collisions. The result shown in the left panel of Fig.3 is limited by statistical uncertainties and do not distinguish between different scenarios for gluon polarization in the proton allowed by polarized DIS data, but tend to disfavor GRSV-max gluon polarization scenario.

The PHENIX experiment presented their double helicity asymmetry of the inclusive π^0 production at midrapidity in polarized $p+p$ collisions. The result shown in the right panel of Fig.3 was compared with GRSV theory calculations, and excluded the GRSV-max model. In order to distinguish the GRSV-std model and calculations with smaller ΔG values, more statistics is necessary.

As a future expectation, both the PHENIX experiment and STAR experiment presented flavor-decomposed quark and antiquark polarization measurement with the weak-boson measurements in forward rapidity at $\sqrt{s}$ = 500 GeV. The PHENIX showed the expectation of their forward muon measurement and the STAR showed that of their forward electron measurement.

2.2. *Orbital angular momentum and DVCS*

The only way which presently we have with a theoretical basis to measure the orbital angular momentum in the nucleon is a measurement of the Generalized Parton Distributions (GPDs). GPDs provide an access to the total angular momentum of quarks, J_q, through Ji's sum rule. GPDs enter in

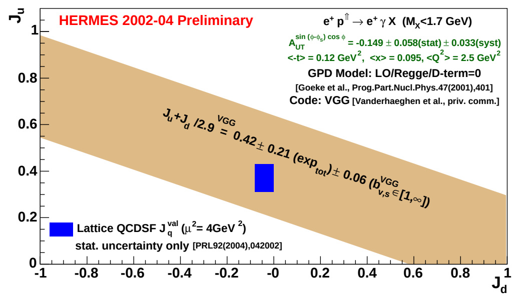

Figure 4. A model-dependent constraint on J_u and J_d obtained by the HERMES experiment and comparison with a quenched lattice-QCD calculation.

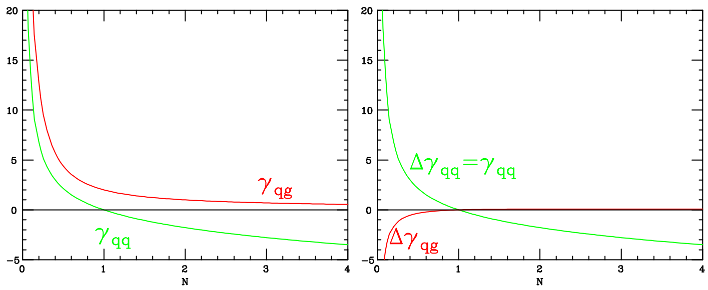

Figure 5. Unpolarized (left) and polarized (right) anomalous dimensions.)

hard exclusive reactions, e.g. Deeply Virtual Compton Scattering (DVCS).

The HERMES experiment has firstly measured the transverse target-spin asymmetry associated with DVCS, $A_{UT}(\phi,\phi_S)$, on the proton. The $\sin(\phi-\phi_S)\cos(\phi)$ term of $A_{UT}(\phi,\phi_S)$ is sensitive to J_q. A model-dependent constraint on J_u and J_d was obtained by comparing the asymmetry and the theoretical predictions based on a GPD model. Figure 4 shows the result and comparison with a quenched lattice-QCD calculation.

2.3. *The state of the art: partial results and global fits*

Inclusive deep-inelastic experiments can only lead to the determination of one linear combination of quark plus antiquark polarized densities, $g_1 \sim \sum_i e_i^2\,(q_i+\bar{q}_i)$ — two, if proton and deuteron targets are available. Also, they only provide a weak handle on the gluon through scaling violations, due to the smallness of the relevant first moments of polarized anomalous

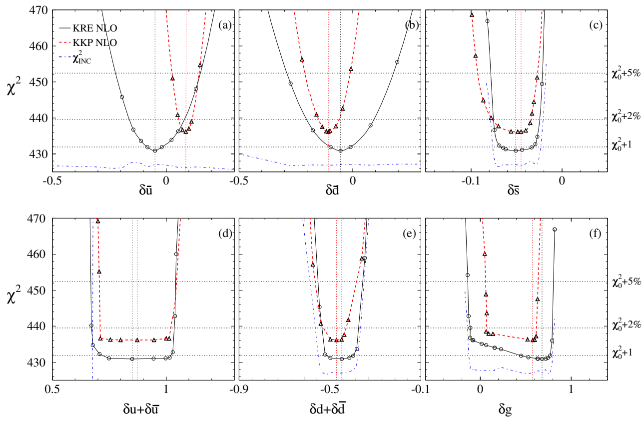

Figure 6. Global fit to inclusive and semi–inclusive deep–inelastic scattering data . (From Ref. [9])

dimension (see Fig 5). Hence, they only determine accurately the isotriplet (Bjorken sum rule), while the singlet quark and gluon first moments are affected by large uncertainties, and there is essentially no information on the total polarized strangeness.[3] Recent more precise inclusive data[5] further improve the Bjorken sum rule and provide some more information on the small x behaviour of the g_1 structure function, but cannot help in improving this situation.

Recent effort has therefore concentrated on trying to extract information from less inclusive observables. Semi–inclusive deep–inelastic scattering (SIDIS) seems especially useful for the determination of individual polarized flavors and antiflavor, by tagging their fragmentation into individual final–state hadrons. At leading perturbative order, one can form combinations of measurable asymmetries which are independent of fragmentation and thus measure polarized flavors and antiflavors directly: specifically, the strange polarized distribution.[6].

However, such a leading–order analysis is only accurate if the dominant contribution to fragmentation into a given hadron comes from the quark carrying the corresponding flavor quantum number: i.e., it assumes the validity of the very OZI rule whose violation we are trying to understand. Indeed, a full NLO fit including all available DIS and SIDIS data[9] (see Fig 6) shows that e.g. the first moment of the anti-up dustributions changes by

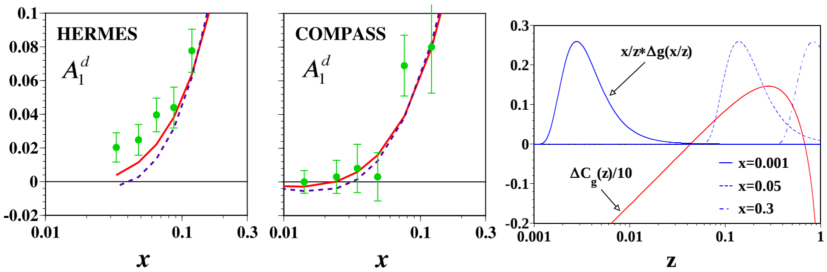

Figure 7. Possible evidence for large $\Delta g(x)/g(x$ at large x from HERMES and COMPASS data. (From Ref. [7])

a factor two from LO to NLO, and can even change sign according to the choice of fragmentation functions. Hence, the remarkably accurate SIDIS asymmetry data are unfortunately of little use on the determination of individual polarized flavors, and in particular strangeness.

Analogously, there are intruiguing suggestions that available information may provide a handle on Δg: for example, a shortfall of a leading–order determination of inclusive DIS polarized asymmetries at medium–small $x \sim 0.05$ may be related[7] to the presence of a sizable positive $\Delta g(x)$ at large $x \sim 0.3$ (see Fig. 7). However, the same effect can also be explained by higher twist contributions[8] (see Fig. 8).

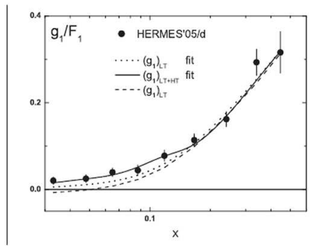

Figure 8. Possible evidence for higher twist contributions from HERMES data. (From Ref. [8])

Whereas RHIC provides us with many processes which are sensitive to Δg, and for which higher twist corrections are small and no further non–perturbative input (such as from fragmentation functions) is required, it remains true that NLO corrections are generally quite large. In particular, polarized K–factors are neither small nor constant (see Fig. 9), and therefore the full available NLO information must be used.[10]

Furthermore, it is important to remember that the scale dependence of the first moment of ΔG is quite strong: at leading order, ΔG evolves as $\frac{1}{\alpha_s(Q^2)}$, so that e.g. is varies by a factor two when the scale

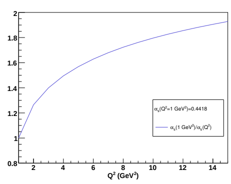

Figure 10. Leading–order scale dependence of the first moment of ΔG.

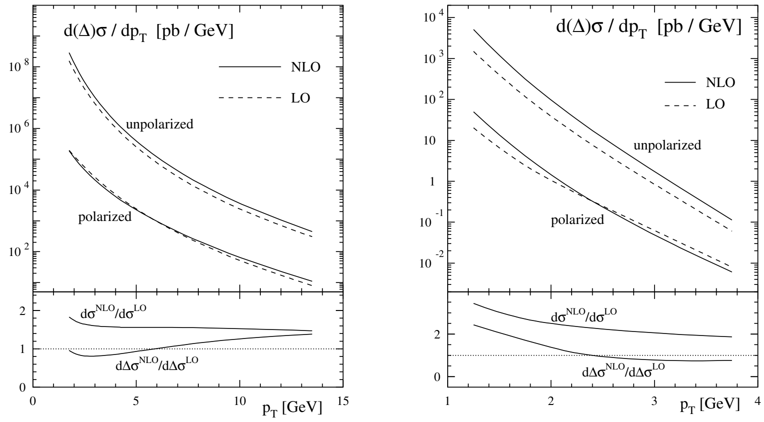

Figure 9. Cross–sections and K–factors for single–inclusive pion production at RHIC (left) at COMPASS (right). (From Ref. [10])

is increased from, say 1 to 15 GeV^2 (see Fig. 10). This, together with the potentially large K–factors, should be kept in mind when comparing different determinations of ΔG, such as in fig. [?]

Therefore, the interesting COMPASS charm production data are likely to play a significant role in the determination of ΔG only if the corresponding NLO corrections (presently available for polarized charm photoproduction and hadroproduction, but not electroproduction) will become available, while double–inclusive large p_T hadrons, for which NLO corrections are unlikely to be determined soon, are unlikely to play an important role.

Because the very many independent processes which will soon be measured at RHIC are sensitive to both the gluon and individual light flavours and antiflavours (see Fig. 11), it is likely that both a direct determination of a_0, a_8 and a handle on the first moment of Δg will soon be possible. Yet, the separation of polarized strangeness and antistrangeness will probably only be possible at a neutrino factory, and a precise determination of ΔG will have to wait for eRHIC. However, it will only be possible to extract this information from the data through a global fit, and no single experiment is likely to e sufficient.

Reaction	Dom. partonic process	probes	LO Feynman diagram	
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg		Jäg Vo
$\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)	Jäg Sig
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$ [67, 73, 74, 75, 76]	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$		Go Co Go
$\vec{p}\vec{p} \to DX, BX$ [77]	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg		Bo
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan) [78, 79, 80]	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$		W
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$		Ka

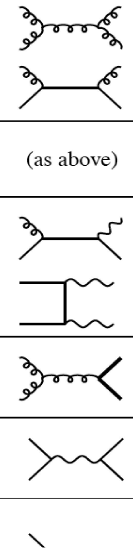

Figure 11. Processes used to determine individual polarized parton distributions. (From Ref. [10])

The conclusion on Δs and ΔG from present–day data is therefore not very different from what it was after the latest and most precise incluisve DIS data[3]: the first moment of the polarized gluon is likely to be positive, though there are some indications that it might be smallish (i.e. $\left(\frac{n_f}{2\pi}\right)\alpha_s(Q^2)\Delta G \lesssim \frac{1}{2}a_0$), and the first moment of the total strangeness is likely to be negative.

3. Transverse spin asymmetries

Many new determinations of transverse spin asymmetries have been performed recently, both in lepton proton and proton–antiproton scattring. Correspondingly, significant progress has been made in the interpretation of these measurements.

3.1. *Experimental results*

From the HERMES experiment, Collins moments and Sivers moments of the transverse single-spin asymmetry (SSA) with the polarized-proton target for semi-inclusive charged pions and kaons were presented. The Collins moments of π^+ show positive asymmetries, those of π^- show positive asymmetries, those of K^+ show small or zero asymmetries, and those of K^- show small positive asymmetries. The Sivers moments of π^+ show positive asymmetries, those of π^- show small or negative asymmetries, those of K^+ show positive asymmetries, and those of K^- show small or zero asymmetries. These results support the existence of non-zero chiral-odd and T-odd structures that describe the transverse structures of the nucleon. First measurement for kaons suggest that sea quarks may provide an important contribution to the Sivers function.

The COMPASS experiment presented their SSA results with the polarized-deuterium target. All asymmetries they showed, both Collins moments and Sivers moments, are consistent with zero. This is an interesting difference from the HERMES results. One possible explanation of the difference is a cancellation of the asymmetries by the polarized proton and the polarized neutron.

From RHIC, the BRAHMS experiment presented their new SSA results of the polarized proton collisions. The SSA of π^+ shows positive asymmetries and that of π^- shows negative asymmetries, both of which are 5-10% in $0.1 < x_F < 0.3$. The SSA of π^+ for $0.2 < x$ is in agreement with twist-3 calculations. The SSAs of K^+ and K^- show positive asymmetries similar each other. This is in disagreement with naiive expectation from valence quark fragmentation. The SSA of proton shows zero-consistent asymmetries and that of antiproton shows positive asymmetries. They also measured cross sections for $\pi^\pm$, $K^\pm$, proton and antiproton in the same kinematic ranges and they were described by the NLO pQCD.

The STAR group presented π^0 asymmetries with their forward and backward detectors. The asymmetries are positive in the forward region, and consistent with zero in the backward region. The p_T dependence of the forward asymmetries shows $1/p_T$ dependence which is expected by the pQCD.

The PHENIX group presented updated asymmetries of charged hadrons at midrapidity, which are consistent with zero. They also presented neutron asymmetries in the most forward region. The asymmetry is higher when there is a charged particle activity in the beam-beam counters.

Table 1 shows a summary of the measured SSAs. A full theoretical understanding of these results is still missing.

HERMES			COMPASS		
proton	Collins	SIvers	deuteron	Collins	Sivers
π^+	$+$	$+$	h^+	0	0
π^-	$-$	0	h^-	0	0
K^+	0	$+$			
K^-	$+$	0			

PHENIX		STAR		BRAHMS	
h^+ midrapidity	0			π^+ forward	$+$
h^- midrapidity	0			π^- forward	$-$
π^0 midrapidity	0	π^0 forward	$+$	K^+ forward	$+$
n 0-degree	$-$	π^0 backward	0	K^- forward	$+$
				p forward	0
				$\bar{p}$ forward	$+$

From the RHIC polarimeter group, high-statistics single-spin asymmety of the proton-proton elastic scattering in the CNI region was presented and compared with the theoretical calculation. It gives a real and imaginary term of the hadronic spin-flip amplitude and it can be zero. They also presented the transverse double-spin asymmetries which are consistent with zero. It suggests the double spin-flip amplitudes are very small. For the proton-Carbon elastic scattering in the CNI region, new beam-energy dependence results were presented.

3.2. *Theoretical progress*

The measurement of large transverse spin asymmetries is theoretically challenging, because these asymmetries are negligible in the parton model: a transverse single spin asymmetry requires a helicity flip, and it is thus $O\left(\alpha_s \frac{m_q}{\sqrt{Q^2}}\right)$. In perturbative QCD, transverse asymmetries in the Collins and Sivers processes can be viewed in two distinct ways: from a parton point of view, as a manifestation of the presence of an intrinsic dependence of parton distributions on transverse momentum, or from an operator point of view as the effect of contributions due to higher–twist operators, specifically twist three quark–gluon correlation.

Recent theoretical progress[11,12] has led to a common picture, where these two point of views can be unified, analogously to what happens for the standard leading–twist collinear factorization. The basis of the unfication is a relation at the level of matrix elements between the transverse–momentum dependent quark distribution, and the relevant twist three operator. Specifically a transverse cross section difference (e.g. in SIDIS or Drell-Yan) can be schematically factorized as

$$\Delta d\sigma \sim \epsilon_{\alpha\beta} s_\perp^\alpha p_\perp^\beta \int \frac{dx}{x} \int \frac{dz}{z} q(z) T_F(x, x - xg), \tag{2}$$

where $q(z)$ is a conventional (collinear) quark distribution and $T_F(x_1, x_2)$ is a twist–three quark-gluon correlation. It can then be shown[11] that the quark–gluon correlation is related by

$$T_F(x, x) = \int d^2 k_\perp |\vec{k}_\perp|^2 q_T(\vec{k}_\perp, x) \tag{3}$$

to the transverse–momentum dependent quark distribution $q_T(\vec{k}_\perp, x)$, defined in terms of a suitable nucleon matrix element of a quark-quark bilinear connected by a gauge link.

One can then show[12] that when $k_\perp \ll Q$ the single–spin asymmetries can be factorized in terms of $q_T(\vec{k}_\perp, x)$, convoluted with a transverse fragmentation function (Sivers function), and a perturbatively computable factor related to soft gluon radiation. The $k_\perp$ dependence of $q_T(\vec{k}_\perp, x)$ can then be computed perturbatively. Substituting the result in the factorized expression, and using eq. (3), the expression eq. (2) for the cross section is reobtained, thus showing the equivalence of the two approches. Furthermore, it can be shown that the transversity structure is universal,[11] in that for instance the Sivers functions for Drell-Yan and SIDIS are both given in terms of a single process-independent function, determined by partonic matrix elements. In fact, the Boer–Mulders $h_1^\perp$ and Sivers $f_{1T}^\perp$ functions can all be expressed in terms of $2n_f + 1$ universal quark and gluon matrix elements.

These results pose powerful constraints on phenomenological studies of spingle spin asymmetries, and they can guide the construction of phenomenological models[13] for the Sivers function.

4. Stretching the boundaries

The widening of the scope of spin physics has led to an extension to the polarized case of lines of experimentation and theoretical analysis which hiterto had been explored only at the unpolarized level.

4.1. *Fragmentation*

The BELLE experiment has measured a significant non-zero asymmetry in the double ratio of unlike-sign pion pairs to like-sign pion pairs (UL/L) produced from $e^+e^- \to q\bar{q}$ reactions in the off-resonance data. The asymmetry is sensitive to the Collins fragmentation function, but it is not very sensitive to favored to disfavored Collins function ratio. By building a new double ratio of unlike-sign pion pairs to charged pion pairs (UL/C), they measured about a half of the UL/L asymmetry. It is sensitive to the favored + unfavored Collins function.

The COMPASS experiment has measured both longitudinal and transverse polarization transfers of Λ and $\bar{\Lambda}$ production. By averaging over the target polarization, they correspond to the measurement of the polarized fragmentation functions, $\Delta_{\Lambda/q}(z_h)$. The longitudinal polarization transfer gives a test of $q\bar{q}$ symmetry of the polarized strange sea in the nucleon. The result showed similar longitudinal polarization of Λ and $\bar{\Lambda}$ in spite of different production mechanism for Λ and $\bar{\Lambda}$. The transverse polarization transfer gives information of initial transverse quark polarization $\Delta_T(x)$ in the nucleon. The result showed a slight tendency to negative polarization transfer. They also showed a result of a small positive spontaneous transverse polarization of Λ and unpolarized $\bar{\Lambda}$.

The STAR experiment showed their prospect to measure the longitudinal polarization transfer of Λ and $\bar{\Lambda}$.

4.2. *Structure functions at low Q^2*

The quark polarization measurement is extended to the low-Q^2 region.

The COMPASS experiment presented A_1^d measurement at low Q^2, $Q^2 < 1$ GeV^2. Since the x coverage and Q^2 coverage are correlated, the data showed g_1^d at small x region, $0.00005 < x < 0.02$, with high precisions. The results of A_1^d and g_1^d are compatible with zero in low Q^2 and small x range. The knowledge of g_1 at low Q^2 is needed to test non-perturbative models, e.g. Regge models and VMD.

The JLab experiments are measuring g_1 in the nucleon resonance region. They are investigating the duality property of quarks and hadrons which shows hadronnic and partonic degrees of freedom can sometimes both be successfully used to describe the structure of hadrons. The equivalence of the moments of structure functions at high and low Q^2 is called global duality if the integration is taken over the whole resonance region, and called local duality if the averaging is taken over the restricted resonance regions.

The CLAS experiment in Hall B has investigated the duality property of g_1^p and g_1^d at low Q^2. The global quark-hadron duality seems to be supported by the measurements. The local quark-hadron duality seems to be supported in some of the resonance regions. The E01-012 experiment at Hall A is measuring g_1 and g_2 on the ^3He target, and The RSS experiment at Hall C is measuring those on the proton and deuteron targets.

4.3. *Resummation*

As we discussed in Sect. 2.3, the computation of NLO corrections to polarized processes has progressed considerably, in patricular due to the needs of RHIC physics. Current and future polarized experiments will also involve processes and kinematical regions where fixed order computations are not sufficient, and this has stimulated the extension to the polarized case of the resummation techniques which have been developed and are currently being applied to unpolarized processes. The relevant all–order resummations fall broadly into two classes: resummation of an inclusive process close to its kinematic threshold, such as Drell-Yan when $Q^2 \to s$, and resummation of the p_T distribution at small p_T. In both cases the all-order terms which have to be resummed are related to the emission of soft gluons, and theit logarithmic enhancement is a leftover of the cancellation of infrared singularities between real emission and virtual corrections.

Threshold resummation for the polarized Drell-Yan process is important for the future experiments at JPARC and GSI discussed previously, because the center–of–mass energy in these facilities is not much higher than the scale of a few GeV^2 at which perturbative computations are applicable. Threshold resummation up to the next-to-leading logarithmic (NLL) level for the transverse Drell-Yan spin asymmetries have been performed in Ref.[14], both at the inclusive level and differential in rapidity; and up to NNLL in the unpolarized case. The resummed K-factors are large, leading to an increase of the cross section by a large factor for invariant masses above ~ 4 GeV^2, but essentially spin independent, so that the asymmetry is only moderately affected.

The resummation of the q_T distribution for the transversely polarized Drell-Yan process is necessary even at RHIC energies, because the unresummed cross section diverges as $q_T \to 0$. A determination of the resummed cross section up to the NLL level [15] shows that unresummed result are in fact unreliable even for intermediate values of $q_T \sim Q/4$, where the cross–section difference is peaked: the resummation gives in fact the dominant contribution, and unresummed results are reproduced only for large $q_T \sim Q$, where the cross section is very small.

The resummation of the q_T distribution has also been performed [16] for the q_T specturm of single–inclusive hadron production in deep–inelastic e–p scattering, in the unpolarized case, for longitudinally polarized electron and proton, for longitudinally polarized incoming electron and outgoing hadron, and both for longitudinally and transversely polarized incoming proton and outgoing hadron. The case of longitudinal ep polarization is relevant for the COMPASS and HERMES experiments discussed in Sect. 2. In this case, one finds that, for the kinematics of these experiments, the impact of resummation effects is again rather large, bit it largely cancels in the asymmetry.

A difficulty in the determination of resummed results is due to ambiguities caused by the fact that at the resummed level the strong coupling hits the Landau pole, a behaviour which is related to the divergent nature of the resummed perturbative series. These ambiguities are moderate in threshold resummation, but become more important in q_T resummation, especially in the region of the peak of the cross section where resummed contribution is very large. For the case of SIDIS, the ambiguity can be as large as the whole resummation, which suggests that a purely perturbative treatment of the process is not really possible, and further undermines its usefulness for determinations of the polarized hadron structure.

In summary, the matching of resummed results to phenomenology will be crucial in the interpretation of future Drell-Yan data from RHIC (q_T distributions), JPARC and GSI.

5. Outlook

References

1. M. Dittmar *et al.*, arXiv:hep-ph/0511119.
2. P. J. Mulders, *these proceedings*, see also Czech. J. Phys. **52**, C27 (2002).
3. G. Ridolfi, eConf **C030614**, 019 (2003) and ref. therein.
4. G. Veneziano, Mod. Phys. Lett. A **4** (1989) 1605.
5. M. Stolarski, *these proceedings*, see also E. S. Ageev *et al.* [COMPASS Collaboration], Phys. Lett. B **612**, 154 (2005).
6. M. Ehrenfried, *these proceedings*, see also A. Airapetian *et al.* [HERMES Collaboration], Phys. Rev. D **71**, 012003 (2005).
7. M. Hirai, *these proceedings*, see also M. Hirai, S. Kumano and N. Saito, arXiv:hep-ph/0603213.

8. E. Leader, *these proceedings*, see also E. Leader, A. V. Sidorov and D. B. Stamenov, Phys. Rev. D **67**, 074017 (2003).
9. R. Sassot, *these proceedings*, see also G. A. Navarro and R. Sassot, hep-ph/0605266; D. de Florian and R. Sassot, Phys. Rev. D **62**, 094025 (2000).
10. M. Stratmann, *these proceedings*, see also B. Jager, A. Schafer, M. Stratmann and W. Vogelsang, Phys. Rev. D **67**, 054005 (2003), B. Jager, M. Stratmann and W. Vogelsang, Eur. Phys. J. C **44**, 533 (2005).
11. P. J. Mulders , *these proceedings*, see also D. Boer, P. J. Mulders and F. Pijlman, Nucl. Phys. B **667**, 201 (2003).
12. F. Yuan, *these proceedings*, see also X. Ji, J. W. Qiu, W. Vogelsang and F. Yuan, arXiv:hep-ph/0602239.
13. L. Gamberg, *these proceedings*, see also L. P. Gamberg, G. R. Goldstein and K. A. Oganessyan, Phys. Rev. D **68**, 051501 (2003).
14. H. Yokoya, *these proceedings*, see also H. Shimizu, G. Sterman, W. Vogelsang and H. Yokoya, Phys. Rev. D **71**, 114007 (2005).
15. H. Kawamura, *these proceedings*, see also H. Kawamura, J. Kodaira, H. Shimizu and K. Tanaka, Prog. Theor. Phys. **115**, 667 (2006).
16. Y. Koike, *these proceedings*, see also Y. Koike, J. Nagashima and W. Vogelsang, Nucl. Phys. B **744**, 59 (2006).